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*Published in:*  
Human Movement Science

*DOI:*  
[10.1016/j.humov.2016.04.002](https://doi.org/10.1016/j.humov.2016.04.002)

Published: 31/08/2016

*Document Version*  
Peer reviewed version

[Link to publication on the UWS Academic Portal](#)

#### *Citation for published version (APA):*

Fu, F., Zhang, Y., Shu, Y., Ruan, G., Sun, J., Baker, J., & Gu, Y. (2016). Lower limb mechanics during moderate high-heel jogging and running in different experienced wearers. *Human Movement Science*, 48, 15-27.  
<https://doi.org/10.1016/j.humov.2016.04.002>

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# Lower limb mechanics during moderate high-heel jogging and running in different experienced wearers

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## Abstract

The aim of this study is to investigate the differences in lower limb kinematics and kinetics between experienced (EW) and inexperienced (IEW) moderate high-heel wearers during jogging and running. Eleven experienced female wearers of moderate high-heel shoes and eleven matched controls participated in jogging and running tests. A Vicon motion analysis system was used to capture kinematic data and a Kistler force platform was used to collect ground reaction force (GRF). There were no significant differences in jogging and running speed respectively. Compared with IEW, EW adopted larger stride length (SL) with lower stride frequency (SF) at each corresponding speed. During running, EW enlarged SL significantly while IEW increased both SL and SF significantly. Kinematic data showed that IEW had generally larger joint range of motion (ROM) and peak angles during stance phase. Speed effect was not obvious within IEW. EW exhibited a significantly increased maximal vertical GRF ( $F_{z2}$ ) and vertical average loading rate (VALR) during running, which was potentially caused by overlong stride. These suggest that both EW and IEW are at high risk of joint injuries when running on moderate high heels. For wearers who have to do some running on moderate high heels, it is crucial to control joint stability and balance SL and SF consciously.

Keywords: moderate high heels; kinematics; wearing experience; jogging; running

## 1. Introduction

The high-heel design has been remaining one of the dominant features of women's footwear. Social and fashion customs encourage the continued use of high-heel shoes (Hong et al., 2005) despite of detrimental effects on the musculoskeletal system, such as lower back pain, ankle sprains, foot pain, hallux valgus and increased predisposition toward degenerative knee osteoarthritis (Barkema, Derrick, & Martin, 2012; Chien et al., 2014; Dawson et al., 2002; Gu et al., 2014; Lee, Jeong, & Freivalds, 2001).

Forcing ankle to a plantar-flexed state, high-heel shoes with narrow supporting base lead to a series of kinematic and kinetic changes of lower limbs during walking. Changes in spatiotemporal parameters have been well documented. Unanimous results revealed that increase of heel height contributed to slower self-selected walking speeds and shorter strides with generally unchanged cadence (Barkema et al., 2012; Cronin, Barrett, & Carty, 2012; Esenyel et al., 2003; Lee et al., 2001; Opila-Correia, 1990a). Most studies on high-heeled gait concerned changes of knee joint. Compared with barefoot or flat shoes condition, walking in high heels has been believed to increase knee flexion during stance phase and at heel strike as compensatory mechanisms attenuating GRF (Ebbeling, Hamill, & Crusemeyer, 1994; Mika et al., 2012; Opila-Correia, 1990a; Simonsen et al., 2012). According to the notion that larger knee abduction moment is associated with the development of knee osteoarthritis (Baliunas et al., 2002), the increase of peak knee abduction moment as the result of increasing heel height has been highlighted (Barkema et al., 2012; Esenyel et al., 2003; Kerrigan, Todd, & Riley, 1998; Simonsen et al., 2012). Studies concerning alternations in ankle joint during high-heeled walking concluded that risk of lateral ankle sprain would increase as heel height increased with increasing plantarflexion and inversion (Foster et al., 2012; Stefanyshyn et al., 2000). Barkema et al. (2012) found systematically increased peak ankle eversion moment during late stance phase with increased heel height. As to hip joint, increased flexion and abduction moments were verified as assistant to attenuate GRF during the first half of stance phase and compensate the reduced ankle plantarflexion moment during push-off (Esenyel et al., 2003; Simonsen et al., 2012). All these studies recruited habitual high-heeled wearers as subjects, accordingly, whether these changes were immediate effects or chronic adaptations have not been fully explored.

Habitual wearers of high-heel shoes were reported to experience long-term adaptations in muscle-tendon architecture, such as increased Achilles tendon stiffness and tendon hypertrophy (Csapo et al., 2010), shortening of gastrocnemius medialis fascicles (Cronin et al., 2012). These adaptations could shift the stretch distribution of muscle-tendon unit away from tendinous tissues toward muscle fascicles during walking, which potentially alters neural activation patterns and decreases muscle-tendon unit efficiency (Cronin et al., 2008; Lichtwark & Wilson, 2007). Opila-Correia et al. (1990b) noted that biomechanical adaptations varied between experienced and inexperienced high-heel wearers including increased knee flexion of the former and exaggerated upper trunk rotations of the latter during stance phase when walking at preferred speed. Other differences as increased abductor and reduced internal rotator moment at hip; reduced ranges of flexion-extension and adduction-abduction at knee; increased external rotation, pronator and external rotator moments at ankle were also observed in self-selected walking task wearing 7.3cm high-heel shoes (Chien et al., 2014). In contrast, studies instructing subjects to walk at fixed speed showed no significant differences in any of spatiotemporal parameters, joint angles and GRF between experienced and inexperienced high-heeled wearers (Ebbeling et al., 1994; Simonsen et al., 2012). One reason concerning significant level of differences may be that the fixed speeds were greater than actual preferred speeds in high-heeled walking.

Studies on changes of GRF in high-heeled gait remain limited. Ebbeling et al. (1994) reported that regardless of wearing experience, the first and second maximal vertical GRFs increased as heel height increased during walking at a fixed speed. Research of Stefanyshyn et al. (2000) obtained similar conclusions from habitual subjects. This study also indicated that there was a threshold for the increase of impact force and maximal vertical loading rate as heel height

increased. Loy and Voloshin (1987) also reported that when heel height increased from 7.6 cm to 8.5 cm, both impact force and loading rate decreased, which might be an injury prevention strategy employed by high-heel wearers.

In general, kinematic and kinetic alternations of lower limb in studies mentioned above were responses to high heels at walking level. However, in modern society, running for a bus, darting across a busy street or dashing to get the last train push most busy women find themselves in need of a little turn of speed every now and then. Previous study demonstrated that the maximal vertical GRF increased linearly from 1.2 BW (body weight) to approximately 2.5 BW during walking and running respectively (Keller et al., 1996). Joint motions of lower limb during walking also significantly differ from that during jogging and running. There are few studies concerning effects of high-heeled jogging and running on lower limb mechanics. Gu et al. (2013) noted that motion range of knee abduction-adduction and hip flexion-extension increased significantly as heel height increased during jogging which may induce high loading force in knee joints. This study only recruited habitual moderate high-heel wearers; however, whether these changes in inexperienced moderate high-heel wearers are the same or even worse and whether increased speed of running has extended effects remain unclear.

The purpose of this study was to clarify differences in lower limb kinematics and GRF between EW and IEW during moderate high-heel jogging and running. It was hypothesized that EW would show faster self-select speeds of jogging and running than IEW; EW would decrease joint instability while increase GRF in comparison with IEW; changes of lower limb joints (range of motions and peak angles) and GRF would increase as speed increased for all wearers.

## 2. Method

### 2.1. Participants

Eleven experienced female wearers of moderate high-heel shoes (EW: age:  $24.2 \pm 1.2$  years; height:  $160 \pm 2.2$  cm; mass:  $51.6 \pm 2.6$  kg) and eleven matched controls (IEW; age:  $23.7 \pm 1.3$  years; height:  $162.3 \pm 2.3$  cm; mass:  $52.6 \pm 4.5$  kg) participated in this test with informed written consent, as approved by the Ethics Committee of Ningbo University. All the subjects were informed of the objectives, requirements and experimental procedures. None of the subjects suffered from any musculoskeletal pathology that might affect normal jogging and running. All subjects were right foot dominant with the European shoe size of 37. EW had worn shoes with narrow heels of 3cm to 6cm height with a minimum of three times per week, six hours per day for at least two years, IEW wore high-heeled shoes less than twice per month.

### 2.2. Experiment protocol and procedure

Subjects completed jogging and running tasks separately at self-selected speed along a 10-meter-walkway. A force platform (Kistler, Switzerland) was fixed in the middle of the walkway and utilized to collect GRF at the frequency of 1000 Hz. The experimental shoe with 4.5cm height heels (Fig. 1) was commercially available. Subjects were given enough time to familiarize themselves with the experimental environment and adjust gait to ensure the right foot stepping onto the force plate completely and naturally before data collection. IEW also performed some progressive training, learning to jog at progressively increasing speeds at which they feel comfortable and safe. The 8-camera Vicon motion analysis system

(Oxford Metrics Ltd., Oxford, UK) was used to capture lower limb kinematics at the frequency of 200 Hz. Subjects were required to wear tight-fitting pants and 16 reflective markers (diameter: 14 mm) were attached with adhesive on the left and right lower limbs, respectively. The marker locations included: anterior-superior iliac spine, posterior-superior iliac spine, lateral mid-thigh, lateral knee, lateral mid-shank, lateral malleolus, second metatarsal head and calcaneus. Five jogging and five running trials were undertaken by each subject. About 5mins were given for subjects to have a rest between jogging and running session.

### 2.3. Data analysis

One gait cycle was defined as the duration from initial contact of one foot to the subsequent contact of the same foot. Data of joint changes in three planes were time normalised to 0 to 100% of the gait cycle. The right side motion during one gait cycle was analysed for all kinematic and kinetic variables. A vertical GRF threshold of 20N was used for the identification of heel strike event. Gait speed was calculated as the anterior-superior displacement of the right anterior-superior iliac spine marker dividing the corresponding time. Stride length (SL) was calculated as the anterior-posterior displacement of the right heel marker during two consecutive heel strike events. Stride frequency (SF) was computed as the inverse of one gait cycle duration. Stance phase percentage (ST/GC) was the percentage of stance phase in one gait cycle. Joint range of motion (ROM) during stance phase was also computed for each joint in three planes. GRF were normalized to body weight (BW). Loading rate was calculated as the slope of the vertical GRF between 20% and 80% of the period from heel-strike to impact force.

### 2.4. Statistical analysis

ANOVA analysis with post-hoc Bonferroni correction was performed to assess the effect of wearing experience combined with gait speed (jogging and running) on spatiotemporal parameters including SL, SF and ST/GC; joints ROM and peak angles; GRF and vertical average loading rate (VALR). Statistical results were considered significant if  $p < 0.05$ . In addition, linear regression analyses were performed to determine the correlation between speed and SL as well as speed and SF for both EW and IEW. All statistical analyses were performed using Stata 12.0 (Stata Corp, College station, TX).

## 3. Result

### 3.1. Spatiotemporal characteristics

Differences in spatiotemporal characteristics are displayed in Table 1. There were no significant differences in each corresponding speed between EW and IEW. Compared with jogging, the speed of running increased significantly for EW and IEW. There were significant differences in SL, SF and ST/GC. SL of EW was significantly larger than that of IEW while SF showed to be smaller. Differences in the effect of speed on SL and SF were also significant. Compared with jogging, EW exhibited significantly larger SL while IEW exhibited both significant increased SL and SF during running. Furthermore, data from regression analyses showed significant differences in the correlation between speed and SL as well as speed and SF between two groups (Fig. 2). For IEW, the speed had significant correlation with SL at jogging level and significant correlation with SL and SF at running level (Table 2 & Table 3); for EW, the speed had significant correlation with SF at jogging

level and significant correlation with SL at running level. IEW showed significantly larger ST/GC than EW at each corresponding speed level (Table 2 & Table 3). Significance of speed effect on ST/GC was shown in IEW. As speed increased, ST/GC increased significantly.

### 3.2. Joint kinematics

Fig. 3 (a-c) shows comparisons of three-dimensional joint changes at ankle, knee and hip during one gait cycle between EW and IEW. Peak angles in three planes during stance phase showed clear differences between EW and IEW while speed effects were not obvious within IEW. In the sagittal plane, peak knee flexion of EW during jogging was significantly smaller than IEW during jogging and running. At hip, peak flexion of EW during running was significantly larger. In the frontal plane, peak ankle inversion of EW during jogging decreased, with  $p < 0.05$ . Also, compared with IEW during running, EW during running showed significantly smaller peak inversion. Significant increase of peak knee flexion in this plane existed in IEW running compared with jogging and EW jogging. Peak hip flexion was shown to be significantly smaller in EW. In the transvers plane, EW showed smaller ankle and knee peak rotation during jogging than running and IEW running. Larger hip peak rotation was found in EW during running in comparison with IEW during jogging and running.

Ankle ROM of EW in the sagittal plane was significantly smaller in comparison with that of IEW. Knee ROM of EW was larger than that of IEW during jogging with significance. EW during running showed significant increase of knee and hip ROMs compared with IEW jogging. Hip ROM during running of EW was also shown to increase than IEW jogging. In the frontal plane, ankle and knee ROMs of EW during jogging showed significant decrease in comparison with IEW jogging and running. There are no effects of whether speed or wearing experience on hip ROM in this plane. In the transverse plane, ROM at knee of EW was significantly smaller than that of IEW running. At hip, EW only showed significant decrease during jogging than IEW running. Speed had no apparent effects on joints ROM of IEW.

At touchdown, ankle of IEW was at a more plantar-flexed position. Significant increase of knee flexion at initial contact was found in comparison between EW jogging and IEW running. Hip flexion of EW during running was significantly larger than that of IEW at both speeds. Also with significance, hip flexion of EW during running increased than during jogging.

### 3.3. GRF and VALR

Table 4 and Fig4, 5 summarize the main GRF and VALR characteristics of EW and IEW. Impact force ( $F_{z1}$ ) showed no significant differences between wearing experience or speeds. The maximal vertical GRF ( $F_{z2}$ ) of EW during jogging was significantly larger than that of IEW jogging. EW during running showed significantly larger  $F_{z2}$  compared with IEW jogging and running.

## 4. Discussion

This study identified long-term effects of wearing moderate high heel shoes on kinematic and kinetic changes in terms of spatiotemporal parameters including SL, SF and ST/GC; kinematics including joint motion characteristics of ankle, knee and hip; kinetics including  $F_{z1}$ ,  $F_{z2}$  and VALR during jogging and running.

Most studies have ignored the possible importance of high-heeled wearing experience (Cronin, 2014). Different from the first hypothesis, EW and IEW showed comparable preferred speeds during jogging and running. However, they performed different SL and SF for a certain speed. Statistical data showed that no matter during jogging or running, IEW adopted higher SF with shorter SL. Similar result that elder women in China with bound feet took more steps and shorter strides compared with those with normal feet when walking at similar speed has been reported (Zhang, Feng, Hu, & Gu, 2015). Chien et al. (2014) noted that in comparison with habitual wearers, inexperienced controls showed less stable body balance during walking. This increased SF with decreased SL may be a strategy adopted by IEW to compensate reduced local dynamic stability through enhancing medial-lateral and backward margins of stability respectively (Hak et al., 2013). However, a limitation of this study is that there is no evidence to prove whether EW possess better body balance than IEW. The next step is to examine the influence of long-term use of high heels on balance control in jogging and running with parameters that could quantify gait stability such as short-term Lyapunov exponent (Dingwell & Cusumano, 2000), margins of stability (Hof, Gazendam, & Sinke, 2005), COM-COP inclination angles and the rate of inclination angle changes (Chien et al., 2014).

As the speed increasing from jogging to running, SL of both groups increased significantly while SF showed significant increase in IEW. Therefore, it can be speculated that EW adapt speed increase with increasing SL while IEW adapt speed increase with increasing both SL and SF. Further, speed showed linear correlation with SL in IEW and SF in EW during jogging. As to running, speed showed linear correlation with both SL and SF in IEW while with SL in EW. These findings from regression analysis suggest that EW adopted SF-dominant strategy while IEW adopted SL-dominant strategy in regulating jogging speed. With speed increasing to running, SL and SF concurrently play the role in regulating speed for IEW. Compared with SF, SL showed more obvious effect with higher value of  $R^2$ . For EW, the increasing running speed was mainly acquired by the increase of SL. The overlong stride during high-heeled running may potentially cause falls or musculoskeletal injuries. Consistent with the concept that contact time decreases with running speeds increase during normal shod or barefoot running (Cavanagh & Kram, 1989; Yokozawa, Fujii, & Ae, 2005), results from IEW in this study also revealed significantly decreased ST/GC as speed increasing. In addition, IEW showed longer stance phase duration in one gait cycle at both speeds, indicating a cautious gait style to deal with body instability.

One might expected greater joint ROMs with faster speed particularly while running on high heels, however, there was in fact no obvious effect of speed on joint ROMs within each group except for the ROM of hip flexion-extension. Hip ROM in the sagittal plane of EW increased significantly during running in comparison with that of EW and IEW during jogging due to the larger peak flexion. Significant change of hip ROM was also observed in the transvers plane. EW presented significantly smaller ROM during jogging than IEW running. Similarly, knee ROM of EW in frontal plane during jogging was shown to be smaller. In the transverse plane, knee ROM of EW during running was significantly smaller. These reduced motions in hip and knee joints of EW may be associated with larger leg stiffness after long-term use of high heels to maintain stability. However, it has been suggested that exaggerated or insufficient stiffness throughout the lower limb would predispose individuals at high risk of injury (Butler, Crowell, & Davis, 2003; Williams, Davis, Scholz, Hamill, & Buchanan, 2004). Too little stiffness may allow for excessive joint motion leading to soft tissue injury,

conversely, excessive stiffness will lead to increased peak forces, loading rates and shock. Knowledge of these indicates that individuals with different high-heeled wearing experience should modify their lower limb stiffness consciously (Butler, Crowell, & Davis, 2003). EW showed significant increase of knee ROM in sagittal plane at both speeds compared with IEW jogging. The larger knee motion mainly results from extension during push-off, which could help to lengthen stride. At ankle, the mobile ankle in sagittal plane of IEW serves as a less effective lever for application of muscle force to the ground, which requires greater muscle work to achieve similar mechanical output generated by triceps surae during the propulsive period (Powell et al., 2014). This is a potential factor exacerbating muscle fatigue and strain injury particularly for IEW. Relatively, EW showed better control of joint motions at both speeds.

Results on peak joint angles support the hypothesis that EW showed limited peak angle except for peak hip flexion and internal rotation during running. However, speed effect was not obvious within IEW. In the sagittal plane, EW showed significantly larger hip peak flexion during running, which may help to lower the centre of mass to enhance body balance as speed increases (Novacheck, 1998). Larger hip flexion at initial contact was also found in EW during running. This has been reported to be a compensatory mechanism to attenuate increases in impact force to prevent injury (Mika et al., 2012; Robbins, Gouw, & Hanna, 1989). In opposition to the statement that habitual wearers had much greater increases in knee flexion during stance phase of walking than the inexperienced (Oplia-Correia, 1990b), this study showed significantly smaller peak knee flexion in EW during jogging. Although larger knee flexion during walking facilitate to maintain balance, extended flexion of IEW during jogging and running may lead to excessive knee extensor moment (Alkjaer et al., 2003; Simonsen et al., 2012) and rectus femoris activity (Mika et al., 2012; Stefanyshyn et al., 2000), both of which are causes of knee overload (Kerrigan et al., 2005; Kerrigan, Lelas, & Karvosky, 2001). The 7% increased extensor moment and 14% increased knee abduction moment were observed respectively in young and elderly women when walking on shoes with a 3.8cm heel height compared with flat shoes (Kerrigan et al., 2005). Researches also proved that large quadriceps forces induced by increased knee flexion would increase proximal anterior tibial shear force which is a major factor of anterior cruciate ligament strain (Beynon et al., 1997; Fleming et al., 2001; Simonsen et al., 2012). In addition, increased knee flexion has been correlated with forward moving of the centre of mass over the larger and more stable forepart of the foot, possibly resulting in larger forefoot plantar pressure (Murray, Kory, & Sepic, 1970). Gu et al. (2013) found significant increase of plantar pressure in the first metatarsal region with heel height increasing during jogging. Knee flexion of IEW at initial contact increased significantly during running than that of EW jogging. Increasing knee flexion is a common occurrence in high-heeled gait to reduce imbalance (Cronin, 2014). As to ankle, EW showed significantly smaller ankle plantar flexion at touchdown, which is prone to landing with the isolated narrow heel.

Overall, joint motions in the frontal plane were more subtle than in the sagittal plane. At hip, IEW showed significantly larger peak abduction at both speeds compared with EW, which possibly induces larger medial-lateral excursion of the centre of mass leading to body instability. At knee, IEW showed significantly increased peak abduction during running than both groups during jogging. Previous study has revealed that increased knee abduction with heel height rising during jogging may increase knee joint loading (Gu, Zhang, & Shen, 2013). It has been calculated that 1% increase in knee abduction moment increases the risk of



progression of osteoarthritis by 6.46 times (Miyazaki et al., 2002). At ankle, EW showed less peak ankle inversion than IEW. One possible explanation as to the reduced inversion is that pronator activity increased after long-term use of high heels (Chien et al., 2014). Compare with inexperienced controls, experienced subjects showed larger ankle pronator moment in walking test (Chien, Lu, & Liu, 2014). Ankle peak inversion increased significantly as speed increased in EW. Coupled with plantar-flexed joint position, larger inversion angle put wearers at high risk of lateral ankle sprain (Payne, Munteanu, & Miller, 2014).

Motions in the transverse plane were more flexible at ankle compared to hip and knee. EW showed significantly less peak ankle and knee external rotation during jogging than both groups during running. These results indicated that regardless of wearing experience, wearers were caught in high incidence of ankle sprain and stress fracture during high-heeled running. Joint instability of IEW could be attributed to weak control ability and that of EW during running was potentially caused by landing with the narrow heel. Another clear consequence of more obvious heel strike pattern of EW was reflected by the significantly larger hip peak rotation during running compared with that of IEW during jogging and running. This may partly reduce excessive knee rotation during running for EW.

During swing phase, EW also showed different gait kinematics from IEW. In the sagittal plane, the maximum hip and knee flexion increased as speed increased, which was linked with larger stride length (Novacheck, 1998). EW showed larger maximum hip and knee flexion compared with IEW. These were in line with the outcome of largest stride length exhibited in EW during running. Additionally, larger hip and knee flexion during swing phase could contribute to avoid tripping caused by low minimum distance between the toe and the ground (Moosabhoy & Gard, 2006). On account of less maximum flexion of the hip and knee, IEW showed slightly less maximum ankle plantar flexion. However, knowledge of toe clearance excursion and the timing of the minimum toe clearance in one gait cycle during high-heeled jogging or running remain absent. Moreover, angle-time curves of EW in the sagittal plane showed an apparent change of hip extension during the second half of swing phase, which related to better avoiding excessive deceleration that would occur at touchdown if the foot was too far ahead of the centre of mass (Novacheck, 1998). In the frontal and transverse planes, differences may be caused by compromised neuromuscular control system which is mediated by central mechanisms (Delahunt et al., 2006). Previous researches have demonstrated that alternations in joint position sense may lead to kinematic changes during gait (Konradsen & Voigt, 2002; Wright et al., 2000). Based on this, larger ankle inversion and external rotation of IEW throughout swing phase during jogging and running could be explained. It might be due to different joint position senses under passive plantar-flexed state while wearing high heels. Similar results were also observed in chronic ankle instability subjects during jogging compared to healthy controls (Chinn, Dicharry, & Hertel, 2013; Drewes et al., 2009). It is important to investigate if joint motions during swing phase have influences on kinetics and kinematics during stance phase. As reported previously, kinematic alternations at mid-swing could decrease impact peak and loading rate during running with sports shoes (Schmitz et al., 2014).

GRF and VALR have both been reported factors leading to running injuries (Cheung & Rainbow, 2014; Lieberman et al., 2010; Murphy, Curry, & Matzkin, 2013). Impact transients are sudden forces with high rates and magnitudes of loading that travel rapidly up the body and thus may contribute to high incidence of running related injuries, especially tibial stress fractures, patellofemoral pain, Achilles tendinopathy, and plantar fasciitis (Nunns et al., 2013;

Revill et al., 2008; Tam et al., 2014; Willson et al., 2014). To our best knowledge, this is the first work to investigate the difference in GRF during moderate high-heeled jogging and running among different experienced wearers. For EW, GRF-time curve is characterized by an initial sharp peak immediately followed by a second peak during shock absorption period particularly in running. The obvious second peak during running is likely to be attributed to immediate and evident slap of the forefoot on the ground followed with heel strike. The “double-shock” force in running may aggravate joint injuries. In contrast, IEW showed relatively easy and fluent rollover of the foot from the heel to forefoot contacting with ground during jogging and running, resulting in one sharp peak at heel strike.  $F_{z1}$  showed no differences across four conditions. However,  $F_{z2}$  of EW during jogging was shown to be significantly larger than that of IEW at the same speed. Moreover, EW also showed significantly larger  $F_{z2}$  during running compared with IEW at both speeds. The increased GRF found in EW appears to contribute to increase plantar flexor and pronator moments at ankle (Chien et al., 2014), which helps reduce ankle instability during push-off. Another obvious difference between EW and IEW was found in VALR. EW showed significantly larger VALR during running, which was largely due to faster reaching to impact force. This may relate to higher acceleration of the foot at touchdown with heel, suggesting that the negative effect caused by strike pattern exceeds the positive effect of larger knee and hip flexion of EW in attenuating impact shock. It has been widely documented that impact force with a fast increasing rate would create a robust shock wave during heel strike, which is then transmitted up to joints and musculoskeletal system (AS Voloshin & Loy, 1994) potentially causing lower limb soft tissues damage and back-pain complaints (A Voloshin & Wosk, 1982; Wosk & Voloshin, 1981) and eventually leading to degenerative joint disorders (Kerrigan et al., 1998).

This study provides a basis for evaluation of lower limb mechanics in moderate high-heeled jogging and running based on wearing experience and also provides information on moderate high-heel shoe design for individuals with different wearing experience. Our findings along with those from Chien et al. (2013) and Luximon et al. (2015) suggested that the small supporting base especially at heel strike was major factor of reduced stability for habitual high-heeled wearers. Despite of wearing experience, however, running on moderate high heels definitely increases risks of knee osteoarthritis and ankle sprain. The heel geometry including height (Gu, Zhang & Shen, 2013; Stefanyshyn et al., 2000), base size (Guo et al., 2012; Luximon et al., 2015) and even angle between the sole and heel etc. should be integrated in high-heel shoes design for individuals with different wearing experience.

## 5. Conclusions

A key finding of this study was that compared with IEW, EW showed reduced joint ROM during stance phase to prevent excessive joint loading except for motions of knee and hip in sagittal plane that respectively aid in propulsion and load attenuation instead. Moderate high-heel shoes placed IEW at a greater risk of joint and soft tissue injury with generally larger peak angles during stance phase. However, the effect of these conservative control strategies adopted by EW partially lost during running in comparison with jogging. As speed increased from jogging to running, EW mainly relied on increasing SL, leading to landing with narrow high heel, which consequently resulted in an extremely high loading rate. From a kinetic perspective, EW also tended to have bone-on-bone injury in high-heeled running. In conclusion, moderate high-heeled wearers who have to run, whether regularly or occasionally,

are putting themselves at high risk of lower limb damage. If having to run on high heels, **even moderate ones**, it is crucial for wearers to control joint stability and strike pattern consciously.

## Acknowledgements

The study sponsored by National Natural Science Foundation of China (81301600), K.C.Wong Magna Fund in Ningbo University, and Zhejiang Xinmiao Innovation Talents Scheme (2015R405084).

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Fig. 1 Experimental shoe with 4.5cm heel

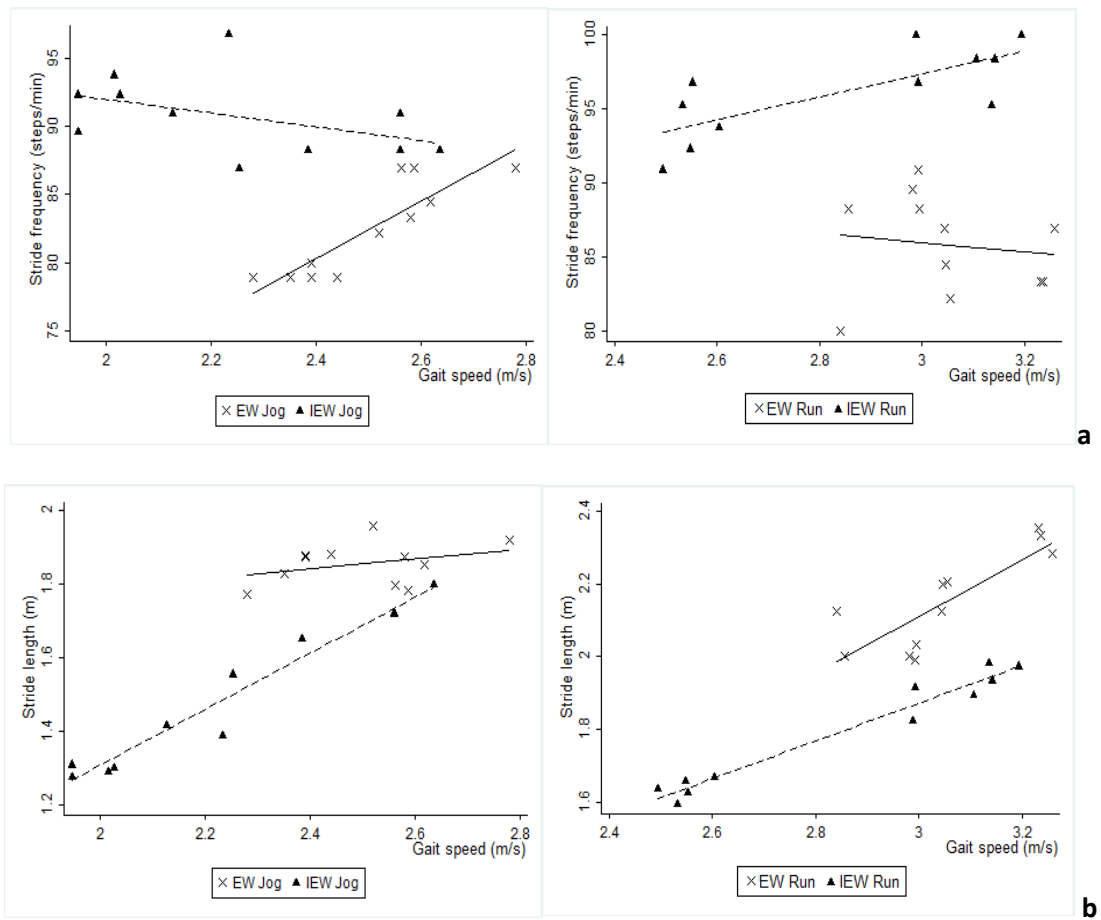


Fig. 2 (a) Regression analyses (Stride frequency is plotted versus speed. Each sign represents the average for each subject for a specific condition.

(b) Regression analyses (Stride length is plotted versus gait speed. Each sign represents the average for each subject for a given condition.)



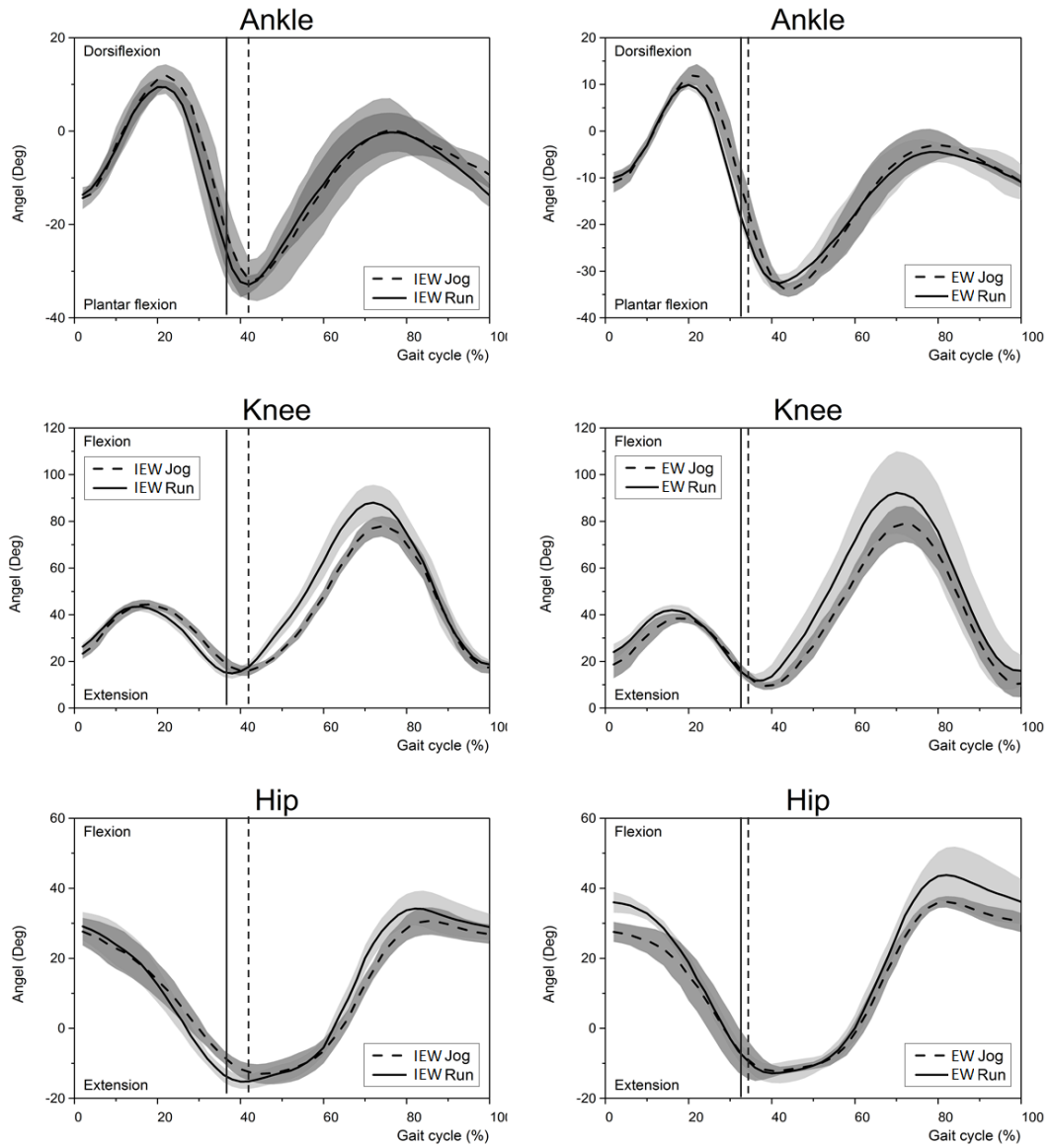


Fig. 3 (a) Changes of joint angles in the sagittal plane (solid and dash straight lines represent the transition from stance phase to swing phase during running and jogging, respectively)

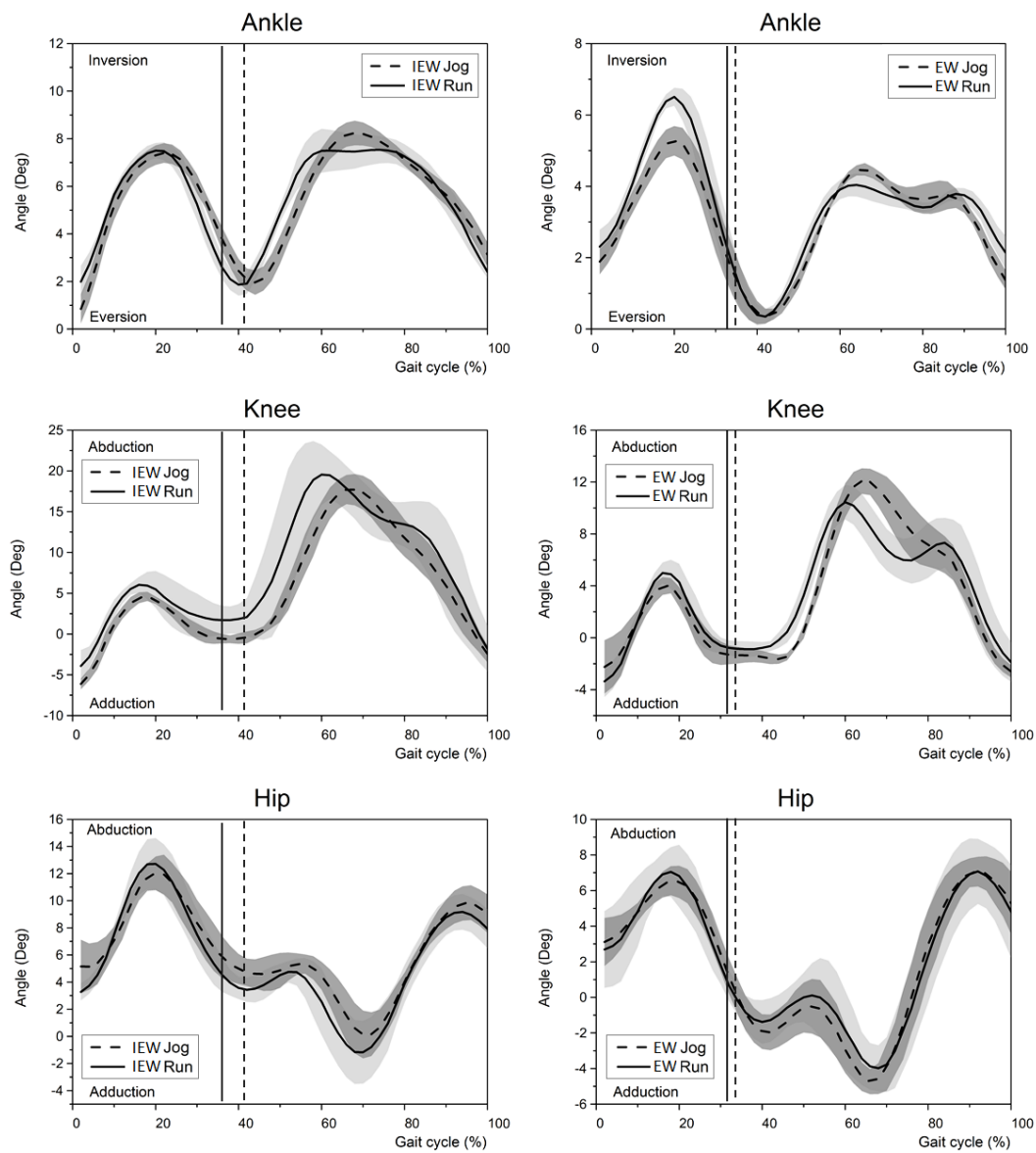


Fig. 3 (b) Changes of joint angles in the frontal plane (solid and dash straight lines represent the transition from stance phase to swing phase during running and jogging, respectively)

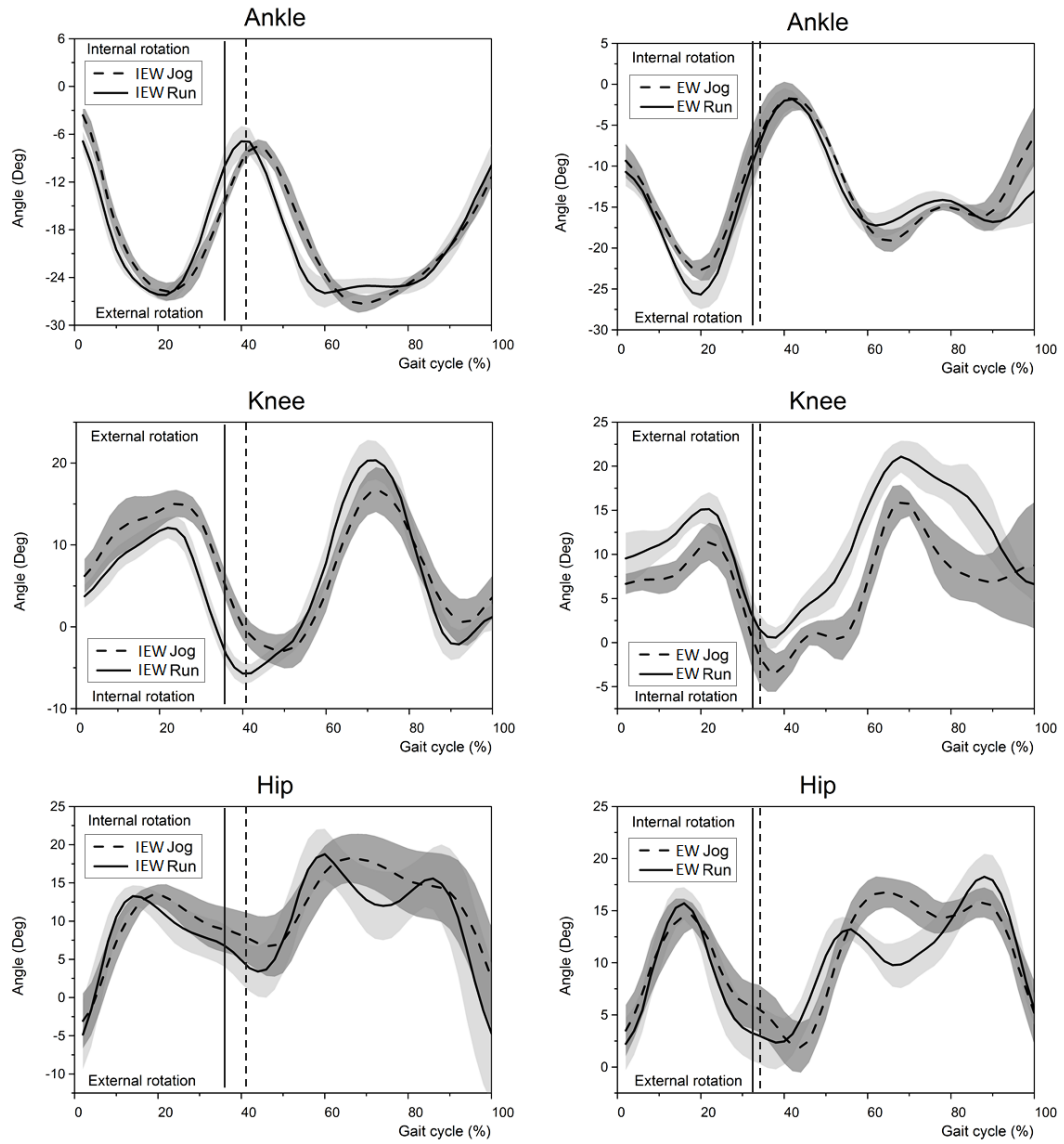


Fig. 3 (c) Changes of joint angles in the transverse plane (solid and dash straight lines represent the transition from stance phase to swing phase during running and jogging, respectively)

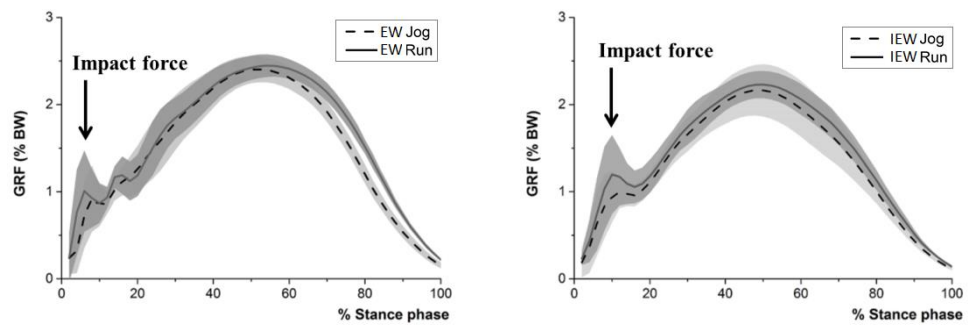


Fig. 4 The GRF of EW (left) and IEW (right) wearers during jogging and running

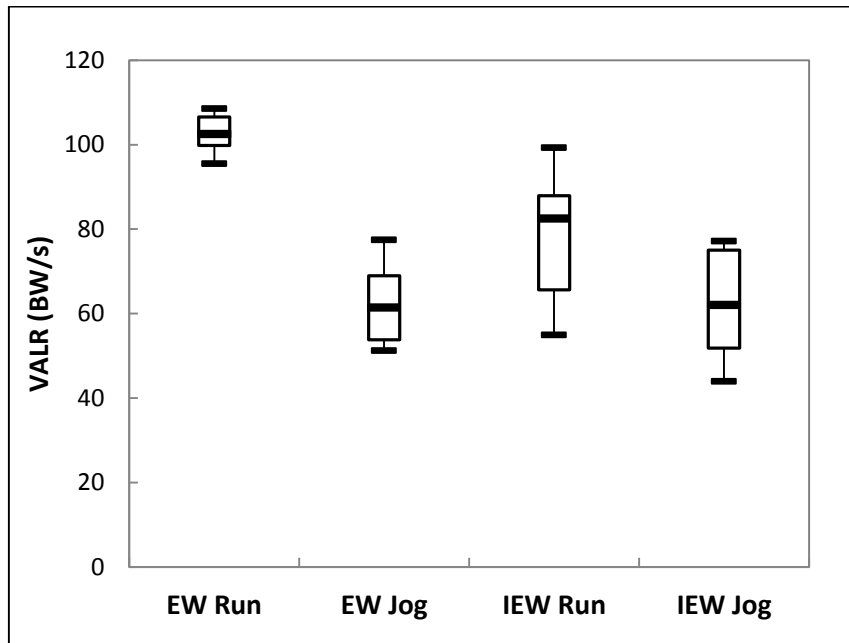


Fig. 5 The VALR of EW and IEW during jogging and running

Table 1. Spatio-temporal parameters and kinematic parameters during stance phase

Parameters		EW		IEW	
		Jog	Run	Jog	Run
Spatio-temporal	Speed(m/s)	2.50±0.14 <sup>§&amp;</sup>	3.05±0.14 <sup>^</sup>	2.24±0.26 <sup>#</sup>	2.84±0.29
	SL(m)	1.86±0.06 <sup>§¶</sup>	2.15±0.14 <sup>^£</sup>	1.49±0.20 <sup>#</sup>	1.79±0.16
	SF(steps/min)	82.43±3.48 <sup>¶&amp;</sup>	85.84±3.39 <sup>^£</sup>	90.74±2.92 <sup>#</sup>	96.16±3.00
	ST/GC	0.35±0.02 <sup>¶</sup>	0.33±0.02 <sup>^£</sup>	0.42±0.03 <sup>#</sup>	0.37±0.01
Sagittal plane ROM	Ankle	39.40±4.44 <sup>¶</sup>	36.16±2.42 <sup>^£</sup>	47.88±2.59	43.89±3.70
	Knee	30.37±2.11 <sup>¶</sup>	30.97±0.86 <sup>^</sup>	29.90±2.67	30.16±1.79
	Hip	39.22±3.73 <sup>§</sup>	46.12±3.88 <sup>^</sup>	39.99±6.06	44.29±5.19
Frontal plane ROM	Ankle	4.90±0.48 <sup>¶&amp;</sup>	5.76±0.46	6.66±0.26	6.30±0.44
	Knee	7.23±2.17 <sup>¶&amp;</sup>	9.19±1.15	11.27±1.20	11.04±1.63
	Hip	8.70±0.68	8.72±1.56	8.80±0.93	10.45±1.78
Transverse plane ROM	Ankle	21.38±2.08	22.32±3.06	22.67±1.05	21.57±0.83
	Knee	16.91±2.21	16.26±1.72 <sup>£</sup>	18.34±1.08	19.97±1.26
	Hip	12.94±2.34 <sup>&amp;</sup>	16.69±3.53	17.74±3.82	19.56±4.40
Sagittal plane Peak	Ankle	12.86±2.10	10.64±0.86	12.94±1.88	10.73±1.02
	Knee	39.47±1.80 <sup>¶&amp;</sup>	42.73±2.13	45.01±2.04	44.16±2.07
	Hip	27.70±2.82 <sup>§</sup>	36.02±2.94 <sup>^£</sup>	27.69±4.00	29.15±4.10
Frontal plane Peak	Ankle	5.51±0.40 <sup>§¶&amp;</sup>	6.80±0.23 <sup>£</sup>	7.51±0.43	7.73±0.33
	Knee	4.57±0.60 <sup>&amp;</sup>	5.84±0.69	5.16±0.58 <sup>#</sup>	7.12±0.89
	Hip	6.80±0.89 <sup>¶&amp;</sup>	7.73±1.01 <sup>^£</sup>	12.62±1.23	13.37±2.07
Transverse plane Peak	Ankle	-23.58±1.05 <sup>§&amp;</sup>	-26.82±1.90	-26.29±1.06	-26.73±0.55
	Knee	12.13±2.19 <sup>§&amp;</sup>	15.95±1.62	15.44±1.52	15.88±0.99
	Hip	15.34±1.53	16.91±1.56 <sup>^£</sup>	14.69±0.95	14.72±0.99
Sagittal plane Touchdown angle	Ankle	-10.95±2.15 <sup>¶&amp;</sup>	-9.97±0.85 <sup>£</sup>	-14.34±2.31 <sup>#</sup>	-13.63±0.72
	Knee	18.72±5.87 <sup>&amp;</sup>	24.06±3.42	23.39±2.22	26.34±1.47
	Hip	27.54±2.84 <sup>§</sup>	35.99±2.96 <sup>^£</sup>	27.61±3.92	29.09±4.10

<sup>§</sup>significant difference between EW jog and EW run;

<sup>¶</sup>significant difference between EW jog and IEW jog;

<sup>&</sup>significant difference between EW jog and IEW run;

<sup>^</sup>significant difference between EW run and IEW jog;

<sup>£</sup>significant difference between EW run and IEW run;

<sup>#</sup>significant difference between IEW jog and IEW run.

Table 2. Results of linear regression for SF.

Variables	R <sup>2</sup>		Prob>F	
	EW	IEW	EW	IEW
SF Jog	0.761	0.197	0.001	0.171
SF Run	0.017	0.568	0.701	0.007

Table 3. Results of linear regression for SL.

Variables	R <sup>2</sup>		Prob>F	
	EW	IEW	EW	IEW
SL Jog	0.112	0.953	0.314	0.000
SL Run	0.677	0.962	0.002	0.000

Table 4. GRF and VALR characteristics of EW and IEW wearers during jogging and running.

	EW		IEW	
	Jog	Run	Jog	Run
VALR (BW/s)	62.40±10.46 <sup>§</sup>	102.66±4.99 <sup>^£</sup>	62.17±14.38	78.15±17.00
F <sub>z1</sub> (BW%)	1.19±0.18	1.35±0.39	1.24±0.24	1.52±0.28
F <sub>z2</sub> (BW%)	2.42±0.12 <sup>¶</sup>	2.51±0.14 <sup>^£</sup>	2.05±0.24	2.27±0.12

<sup>§</sup>significant difference between EW jog and EW run;

<sup>¶</sup>significant difference between EW jog and IEW jog;

<sup>^</sup>significant difference between EW run and IEW jog;

<sup>£</sup>significant difference between EW run and IEW run.